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DESIGN AND FABRICATION OF A QUENCH-FURNACE

FOR THE INSTRON TENSILE TEST INSTRUMENT

A THESIS

Presented to

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William Gaither Holley

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DESIGN AND FABRICATION OF A QUENCH-FURNACE

FOR THE INSTRON TENSILE TEST INSTRUMENT

Approved:

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Finally I would like to thank my parents, whose financial support and encouragement have aided greatly.

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SUMMARY

A special quenching device to rapidly cool a 0.02 square inch cross sectional area tensile test specimen mounted in a special vacuum furnace on the Instron Tensile Testing Machine was designed and built. The specimen can be cooled 65 degrees centigrade in five seconds or 265 degrees centigrade at an air coolant flow rate of 20 cubic feet per minute. The cooling can occur while the test specimen is mounted to the tensile tester under any desired stress below 15,000 pounds per square inch. The mechanism design evolved from the need for such a cooling device to quench aluminum-copper alloy test specimens under tensile loads in the solidus temperature region.

A cylindrical electric resistance furnace was built using the Instron power supply and temperature control. The specially designed and built vacuum chamber--cooling device unit is mounted onto the standard fittings of the Instron Instrument and passes through the core of the furnace. Two pipes descend through the vacuum capsule parallel to the pulling assembly and deliver a coolant to the test specimen through a slot cut in each pipe. A compressed gas is used for coolant with air, argon, or helium recommended.

A series of experiments was run to determine the workability and operating characteristics of the instrument. These showed that the furnace had a six inch uniform temperature zone where, at 615 degrees centigrade, a temperature variation of only plus or minus one degree centigrade existed. A dummy specimen, mounted in the test instrument was used to

determine the effectiveness of the cooling device. Tests showed that at any temperature between 615 and 250 degrees centigrade specimen cooling rate reached a maximum less than one second after quenching began, and decreased as the specimen temperature fell. A single, general curve was drawn to show cooling rate between 615 and 80 degrees centigrade at a cooling air flow rate of 20 cubic feet per minute.

CHAPTER I

INTRODUCTION AND BACKGROUND

Design Requirements

A special quenching device for a vacuum furnace is to be designed and built. It will be capable of rapidly cooling a tensile test specimen from a temperature of 600 degrees centigrade while the specimen has a specified load applied. The apparatus is to fit on the Instron Tensile Testing Instrument and will consist of a special furnace with vacuum capsule to contain the test specimen and cooling arrangement. All the equipment must be made compatible with existing instrumentation.

Potential Use

Recently a series of experiments on deformation of aluminum-copper alloys in the solidus region were performed at The Georgia Institute of Technology[1,2]. Tensile tests of the alloys were made at elevated temperatures using the Instron Tensile Testing Instrument. Under the existing system, the specimen was inserted in a vacuum capsule in the furnace, heated until a uniform stable temperature was attained, connected to the Instron Instrument while still in the furnace, and tensile tested.

Once fracture occurred, however, cooling was a problem. The vacuum capsule had to be flooded with an inert gas, disconnected from the machine, removed from the furnace, and set aside to cool. After the capsule was removed from the furnace it cooled at a rate of approximately 35 degrees centigrade per minute. Approximately one minute was needed to remove the capsule from the furnace before cooling was initiated.

The tensile tests had been conducted in the solidus temperature region of the aluminum-copper alloys. Since microstudies were made of the fracture area, and the microstructure is probably modified after completion of the tensile test, it becomes important to cool the sample as rapidly as possible once the experiment is completed. Allowing the fractured specimen to remain above the solidus for even a short time influences distribution of the liquid second phase which is believed to be changed by a tensile stress. The existing cooling system did not cool the test specimen rapidly enough.

Two features would improve the testing procedure: first, allowing the specimen to be put under a tensile stress in the solidus temperature range and then allowing rapid cooling while the sample remained in tension; second, increasing the cooling rate of the specimen and initiating cooling immediately upon specimen fracture.

To allow cooling while the specimen was still mounted on the Instron Instrument, and to increase the cooling rate, a new piece of equipment had to be built. A new electric furnace and vacuum capsule were made. A means had to be provided for inserting cooling tubes in the capsule that would concentrate a cooling medium on the specimen and allow external control of the cooling process. Materials had to be selected that would withstand temperatures up to 700 degrees centigrade, and moderate thermal shock.

Design Considerations

Every design is unique. Special problems inherent in any design must be weighed and considered in relation to each other before a final plan is made or a working machine built. For this problem six principal factors were considered:

1. Maintaining a set elevated temperature for the duration of the test.

2. Obtaining a rapid cooling rate for the sample.

3. Thermal shock in the vacuum tube.

4. Thermal shock in the test specimen.

5. Strength and corrosion properties of the instrument parts at temperatures in the vicinity of 700 degrees centigrade.

6. Method of applying load to specimen.

These considerations had to be merged together to form a design that would accommodate all the general specifications.

CHAPTER II

EXISTING EQUIPMENT

It was necessary to make the design compatible with existing equipment. Earlier experiments, which necessitated this equipment change, made use of an Instron Tensile Testing Instrument. This instrument was equipped with electronic controlled resistance furnaces, vacuum capsules, and necessary vacuum pumping equipment. The basic machine is shown in Figure 1. The individual components that provided a framework for the design are discussed below.

Load Weighing System

The Instron Instrument uses interchangable load cells to measure the load applied to the sample. A "C" cell with a full scale deflection of 50 pounds, a "D" cell with a full scale deflection of 1,000 pounds, and a "F" cell with full scale deflection of 10,000 pounds are available for use with the system. All cells can be adjusted to give a smaller full scale range. Of particular interest is the "D" cell which has full range of 20, 50, 100, 200, 500, and 1,000 pounds. Accuracy is rated at better than plus or minus one-half of one per cent of full scale. The method of measurement is by a series of strain gauges attached to a torsion bar. These gauges are connected so as to form a wheatstone bridge and are energized by a constant A.C. voltage. Deformation of the bar unbalances the system and a resulting voltage is produced. This signal is then amplified and sent to a chart recorder or oscilloscope. If needed, the signal is

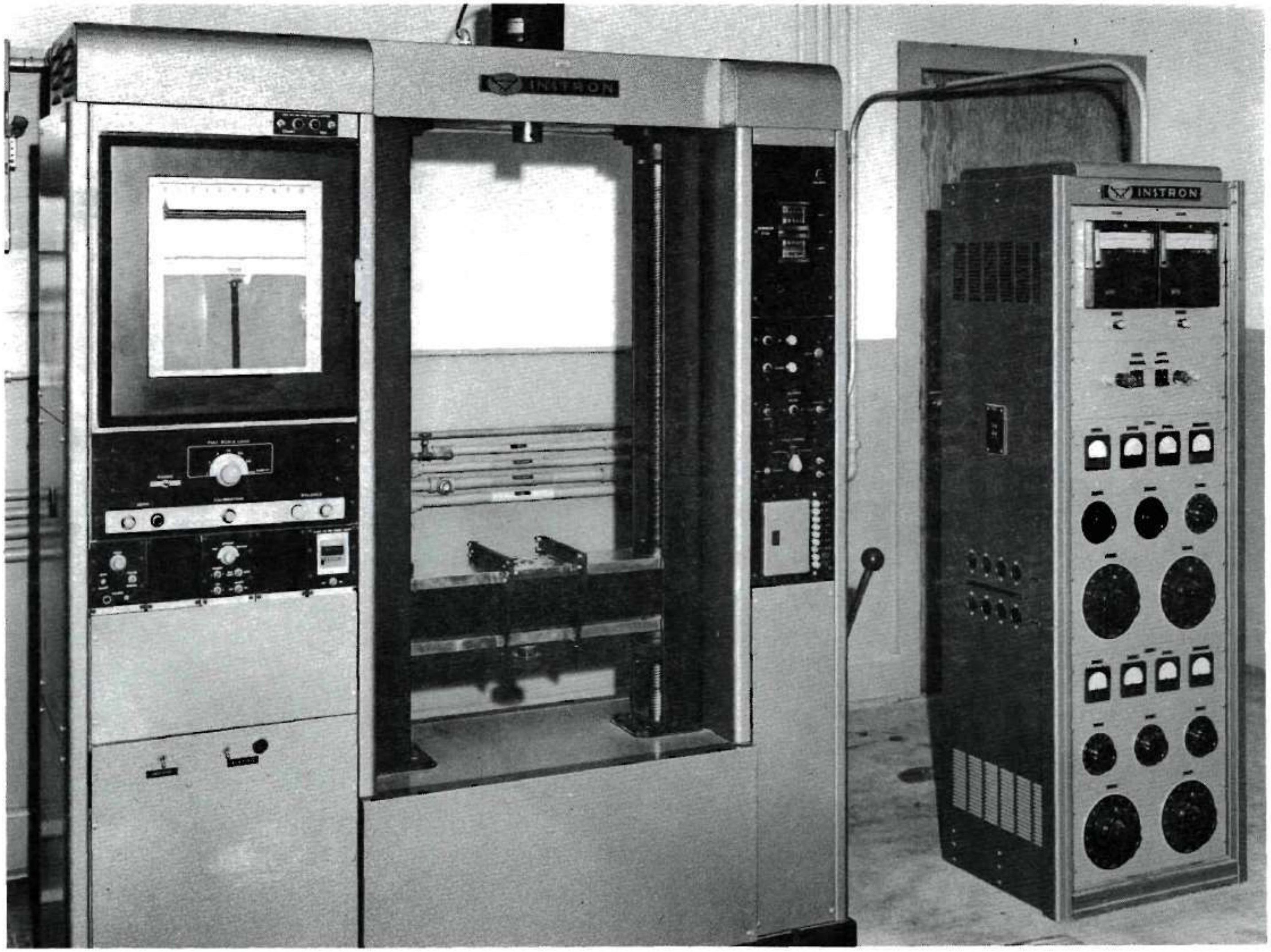


Figure 1. Instron Tensile Testing Instrument.

also sent to a control unit on the machine. A set of weights is available for machine calibration.

Drive System

A movable crosshead is driven by two vertical screws with motion controlled by a servomechanism system. A reference selsyn drive of low mechanical inertia responds to an error signal to correct crosshead motion and thereby gives a fast and accurate response to the large inertia main drive. A preset cam-follower mechanism enables crosshead reversal at a maximum (or minimum) load so that a specified load can be maintained under relaxation conditions. Both manual and automatic controls provide a wide variety of crosshead speeds. Provided maximum load does not exceed 2,000 pounds, speeds of 0.02, 0.05, 0.10, 0.20, 0.50, 1.0, 1.2, 2.0, 5.0, 10, 12, and 20 inches per minute can be achieved.

Chart Recorder

The Leeds and Northrup Graphic Recorder is driven synchronously, although independently of the main drive. It is therefore possible to attain a ratio of chart speeds by a gear mechanism having a direct relation to crosshead travel. The pen of the recorder was found to require 0.21 seconds to travel full scale. The complete load weighing system has a rated response of 0.75 seconds for zero to full scale load.

High Temperature Equipment

Although the system was supplied with a dual-furnace temperature controller, two furnaces, and two vacuum capsule units, only the temperature controller could be used. This controller, when used in conjunction with a platinum-platinum rhodium control thermocouple, regulates furnace temperature within plus or minus two degrees Fahrenheit. An "ON-OFF" type controller supplying high power during the "ON" cycle and slightly less power during the "OFF" cycle regulates the furnace temperature. The power output of the controller can be varied by adjusting a system of variacs. Both "ON"and "OFF" cycles can be set to give distinct power outputs so that the "OFF" cycle will give a smaller power output than the "ON" cycle rather than no output at all. An anticipator adds auxillary EMF to the thermocouple circuit and prevents a temperature overshoot of the furnace. Power is supplied through three variacs which heat separate regions in the furnace. Since power input to each of the regions can be varied, a longer length of uniform temperature can be attained than would be available in a single winding furnace. The controller is set to allow a maximum working temperature of 2,200 degrees Fahrenheit. Each of the power outlets to the furnace are fused at five amperes.

Vacuum System

The vacuum equipment that is available can be used with only slight modification of the piping arrangement. The Cenco Hyvac 14 Pump and portable thermocouple gauge are described.

Cenco Hyvac 14 Pump

This is a two-stage, series-connected, mechanical vacuum pump. It is rated at 1.05 liters per second at one micron of mercury. Its guaranteed blank off vacuum is 0.1 microns of mercury.

Thermocouple Gauge Control

A thermocouple gauge inserted in the vacuum system is used to monitor pressure. The control is a portable instrument which gives pressure indications between 500 and 2 microns of mercury. The gauge and control unit serve as a system leak detector at pressures less than 200 microns.

CHAPTER III

DESIGN COMPONENTS

Furnace

A resistance wound electric furnace is used to heat the test specimen. The unit is constructed of a two and one-half inch inside diameter fused alumina core. This core is wound with three sets of chromel "A" high resistance wire, which are surrounded by fused bubble alumina insulating brick, a sheet aluminum cover, and is mounted on a sliding base. The base fits onto the crosshead of the Instron Tensile Testing Instrument and uses the Instron Temperature Control Unit as a power supply and temperature regulator. A cross section of the furnace is shown in Figure 2.

Resistance Heating Elements

The choice of a heating element material was based on the following criteria: resistivity, chemical stability at elevated temperature, melting point of the alloy, thermal expansion, high temperature strength, and operating temperature range of the furnace. Fabrication and price were also considerations.

Chromel "A," a nickel-chromium high resistance alloy, was chosen. This alloy is acceptable for use in oxidizing atmospheres up to 1,150 degrees centigrade[3], is easy to form at room temperature, and has proved to be a sucessful choice in similar applications[4]. As supplied it has a rated resistivity of 650 ohms per circular mill foot.

The Instron Temperature Control Unit supplies power through a set

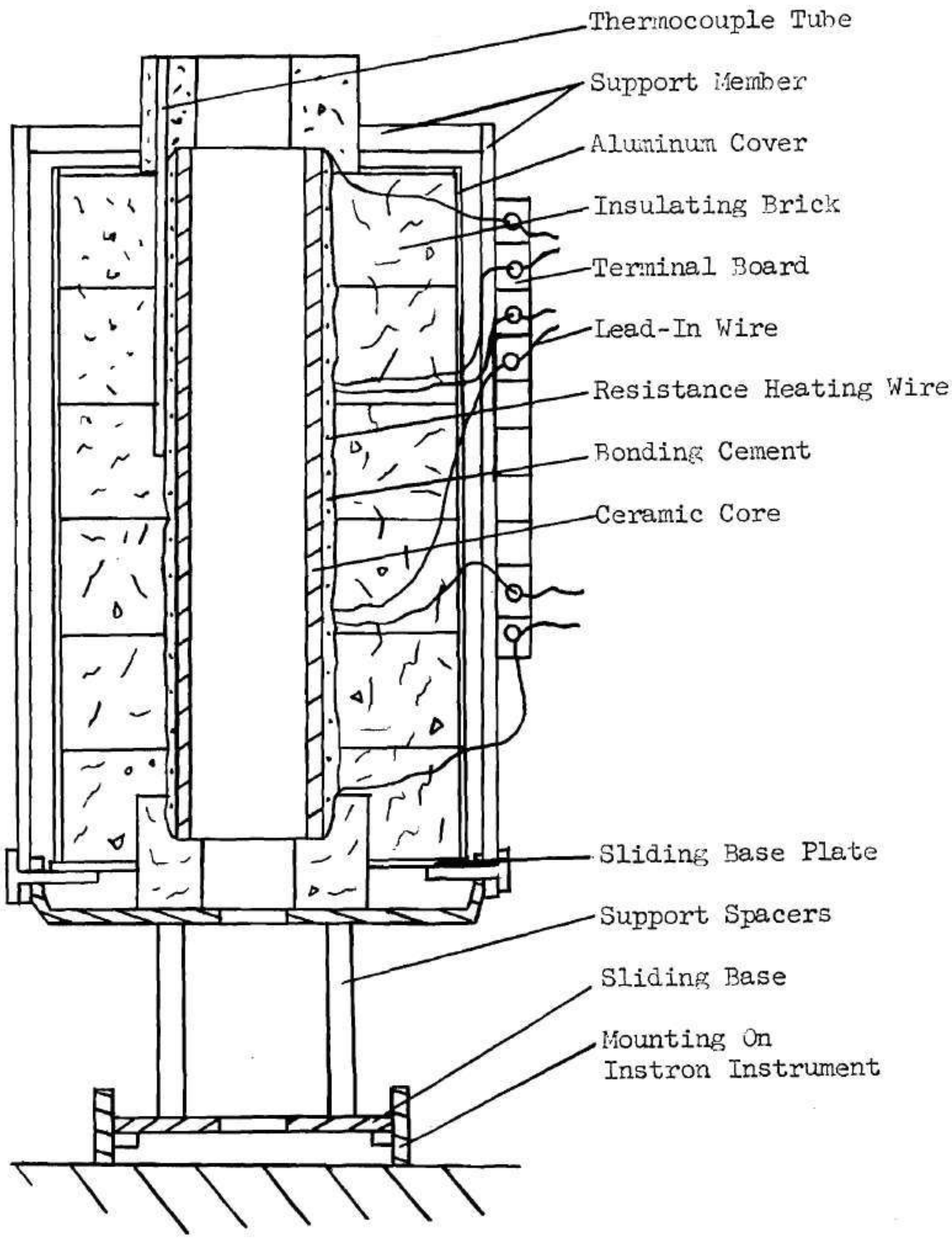


Figure 2. Furnace Cross Section

of variacs. Current passes through a "high" or "low" variac which allows two different power settings for the entire set of windings. Three parallel variacs then further modify the voltage so that three separate outputs can be handled. The winding arrangement enables three separate zones to be constructed, each with an individual winding. The superiority of the three winding system to that of a single winding was fully demonstrated during furnace calibration. For detailed explanation of the furnace calibration see Appendix A.

Each set of windings receives line voltage through a circuit fused at five amperes. Calculations show that for maximum power a 22 ohm resistance is needed in each circuit. Since the wire was wound around a grooved core, and each winding covered five inches of furnace core, 23.7 feet of wire were needed for each winding. A 22 gauge chromel "A" wire was used for winding, and provided a resistance of 23.5 ohms in each circuit. This gauge is satisfactory for long life[3] at working temperature. Four pieces of this wire are wound together to form a lead from the terminal board to the core.

Ceramic Core

Furnace cores are traditionally built of a refractory ceramic. They provide both support for the windings and uniform distribution of heat. Because of their mass, they help to stabilize temperature.

A fused alumina tubular core is used. It is physically and chemically compatible with chromel "A" resistance alloy and may be used at temperatures up to 1,850 degrees centigrade, although the alloy will melt at a lower temperature. The tube is 15 inches long, three and 3/64 inches in diameter, with a bore of two and one-half inches. External grooves assure uniform and proper spacing of the resistance wire. Norton Company manufactures the tube from a 90 per cent alumina mixture fired at 1,450 degrees centigrade.

Refractory Cement

A refractory cement is used to bond the resistance windings to the tubular core. A low maturing temperature, fine grain, fused alumina mixture produced by Norton Company was chosen. This cement is compatible with nickel chromium alloys and has a maturing temperature of 700 degrees centigrade and a maximum allowable temperature of 1,200 degrees centigrade.

Insulation

Fused bubble alumina brick is used for insulation because of cleanliness, ease of fabrication, and superior insulating properties. Since brick is not a loose filler, it can support weight and maintain a rigid shape thereby eliminating the need for a strong outer cover. The three inch minimum thickness of insulation is adequate for maintaining a 700 degree centigrade temperature in the furnace.

The bubble alumina brick were manufactured by Carborundum Company and have a thermal conductivity of 84 BTU per hour foot degree Fahrenheit at 2,200 degrees Fahrenheit. With this high insulating property and low density, fast heating is anticipated. Manufacturer's literature indicated the brick could be cut and shaped with ordinary brick cutting tools.

Installation

The entire furnace is mounted to a base plate which slides on and off a slider attached to the crosshead of the Instron Instrument. This allows the furnace to be positioned properly for use with the vacuum capsule.

The lead-in wires from the furnace windings are attached to a terminal board mounted on the furnace unit. Fourteen gauge electrical wiring connects this terminal board to the power supply.

A platinum-platinum ten per cent rhodium thermocouple is mounted in the furnace between the ceramic core and the insulating material, located near the center of the furnace core and used with the temperature control unit. By supplying an EMF to the control unit, furnace temperature can be stabalized over long periods of time by electronic comparison of this input to a temperature set on the unit. Precise specimen temperature must be measured by a special thermocouple inserted in the vacuum chamber. The control thermocouple reads only the temperature on the outside of the ceramic core and will not measure correctly the temperature where the specimen is placed.

Testing and Calibration

A series of tests, described in Appendix A, was run to determine operating characteristics and temperature distribution in the furnace. These tests showed that at a control setting of 1,250 degrees Fahrenheit, and in an air atmosphere, a uniform temperature zone six inches long existed. In this zone temperature was isothermal within plus or minus one and one-half degrees Fahrenheit. Additional calibration may be necessary to determine an extended isothermal zone in a specimen under test conditions.

Operation

The entire furnace unit is first mounted on the crosshead of the Instron Tensile Testing Instrument by sliding the base into the special furnace adaptor. The power leads are then connected to the power supply. The platinum-platinum ten per cent rhodium thermocouple is inserted into the furnace through a special hole in the furnace top and plugged into the temperature control unit. Since the furnace is constructed with two distinct sides, each containing one-half of the brick insulation, and mounted on a sliding base plate (Figure 2), the sides should be inspected to see that they fit firmly against the core and close to each other.

The power is switched to the "ON" position. For a setting of 1,250 degrees Fahrenheit the following procedure is recommended. The "high" control is switched to full load and the "low" control is set to a reading of approximately 110 volts. The three variacs controlling the separate windings are then set so as to give the following current readings: top, 3.95 amps; middle, 3.55 amps; bottom, 4.40 amps. Using these settings a zone of uniform temperature is expected between points 6 1/2 inches and 12 1/2 inches below the top of the furnace.

Vacuum Chamber - Cooling Device

The main part of the mechanism consists of five principle parts which are inserted through the furnace and mounted on the Instron Instrument as a unit. These parts are diagrammed in Figure 3. The test specimen is the central object of interest with specifications for its manufacture being given in Appendix B. A pulling assembly supplies mounting for the test specimen and is inserted into a cylindrical housing that provides a vacuum chamber. Two delivery pipes provide a mechanism for blasting a stream of cold air on the heated specimen. Thermocouples inserted through the top and bottom of the pulling assembly form a temperature monitoring system.

Pulling Assembly

The test specimen is attached to the Instron Instrument through a

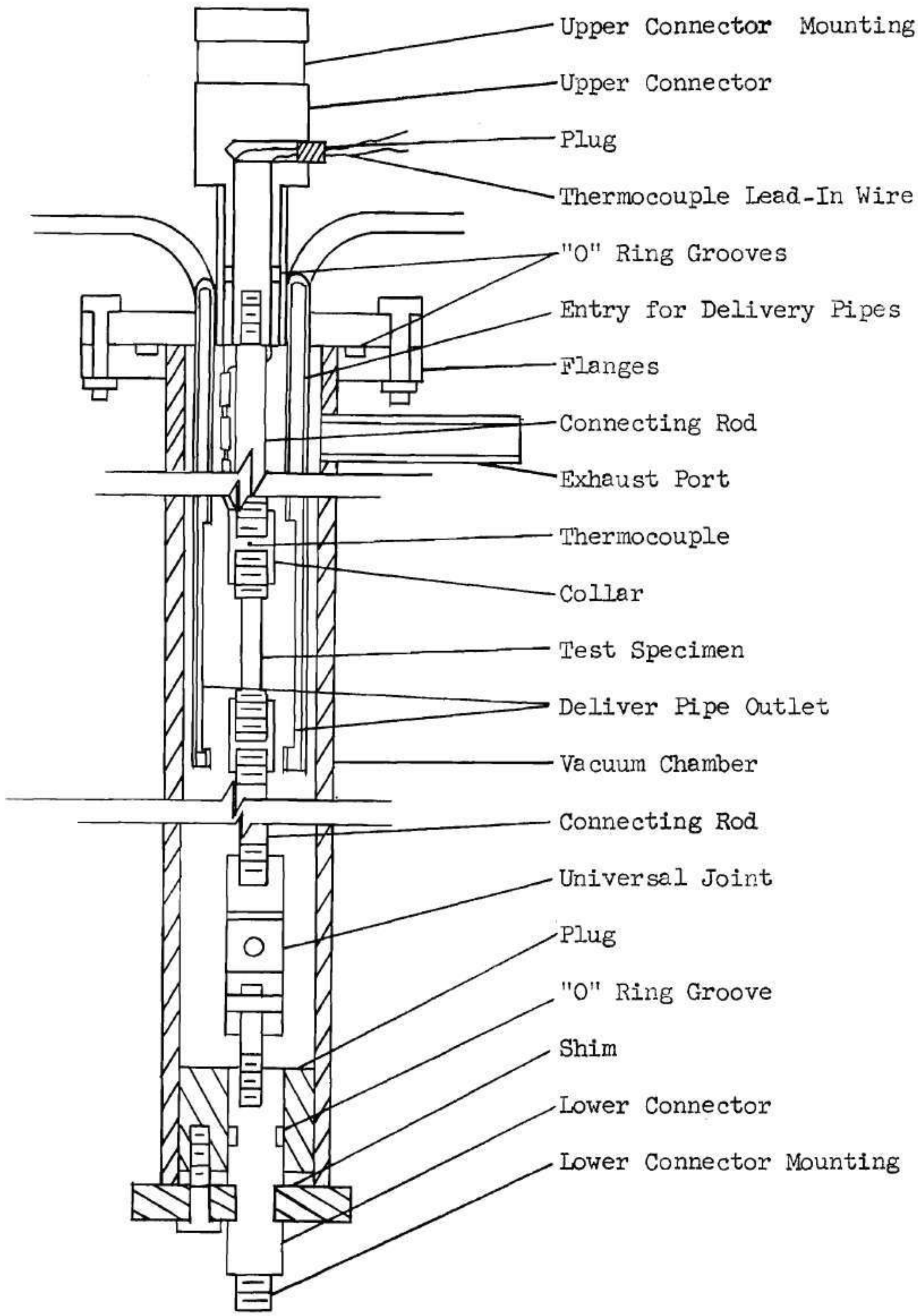


Figure 3. Vacuum Chamber Cooling Device

pulling assembly which consists of two collars into which the test specimen is mounted, two transmitting rods, a universal joint, and an upper and lower connector that gives a moving, but vacuum tight fit, with the vacuum chamber. The upper and lower connectors mount into the Instron Instrument, the lower connector fitting into a threaded mounting on the crosshead and the upper connector fitting into a pinned collar.

The entire pulling assembly is constructed of corrosion resistant materials. The two mounting collars and the two transmitting rods are made of Inconel and retain high strength in the 600 degree centigrade range. Easier machining 304 stainless steel is used for the remaining parts which are not subjected to temperatures in excess of 250 degrees centigrade. Oxidation caused by contact with air heated to 650 degrees centigrade by the furnace will not appreciably affect the useful life of the Inconel or 304 stainless steel parts.

The universal joint provides a means for lining up the pulling assembly during mounting in the vacuum chamber. By assuring a vertical pull by the Instron Instrument, the joint makes manufacture of the entire assembly less critical.

At operating temperatures, that is when the sample had been heated to the 600 degree centigrade range, the pulling assembly will safely tolerate loads up to 300 pounds which is equivalent to a stress level of 15,000 pounds per square inch in the 0.02 square inch test specimen. Above this design limit failure of pulling assembly parts may result although by eliminating the design safety factor loads up to 500 pounds (25,000 pounds per square inch) may be imposed. An excess of 500 pounds will most probably result in failure of the pulling assembly.

Vacuum Chamber

A vacuum chamber surrounds the test specimen and pulling assembly. The chamber consists of an Inconel pipe with a silver soldered plug at one and a flange at the other. A plate bolted onto the flange has a special fitting through which the pulling assembly enters the vacuum chamber. The assembly likewise passes through the bottom plug but is anchored to this plug so that the moving seal functions only during assembly, not during tests. "O" rings are used for seals between the bottom plug and pulling assembly, the plate fitting and pulling assembly, and plate and flange fittings. The "O" rings are made of Buna N Rubber and will operate to 350 degrees Fahrenheit. A high temperature vacuum grease is used on these rings.

An exhaust port is mounted near the top of the Inconel tube and provides a fitting for attaching a lead to the vacuum system. The chamber will support a vacuum of two microns.

Inconel was chosen as the material for parts of the vacuum chamber subjected to temperatures in the 600 degree centigrade range. No deformation or warpage of the chamber was noticed during the proving tests and the system maintained a vacuum of less than two microns at 600 degrees centigrade.

Quenching Mechanism

The test specimen is cooled by a blast of cold air directed on it from two Inconel pipes. These pipes, which are silver soldered to the removable plate that forms the top for the vacuum chamber, extend down through the chamber to the general vicinity of the specimen. There the ends have been plugged and a slot 1/8 by 3 inches cut in each of the pipes.

This arrangement is diagrammed in Figure 4. The two pipes are arranged so as to blast air at the specimen from two directions and eliminate a lee side on the sample. The two pipe arrangement thereby minimizes warpage that would result from a temperature gradient existing if cooling gas was forced across the specimen from one direction only. Such a gradient would produce bending moments in the specimen and would result in a much greater unknown stress level in the specimen and possible permanent warpage. Air flow passes over the specimen and then out of the vacuum chamber through the exhaust port. The heated air is dumped directly into the atmosphere rather than passing through a vacuum pump on the exhaust line.

Specifications require that the specimen be cooled 50 degrees centigrade in the first five seconds of cooling from a temperature of 600 degrees centigrade. Prior to any experimentation the problem was investigated analytically to see if this cooling rate could be attained. The analysis, discussed in Appendix C, indicated that the specified cooling was possible. Experimentation on a prototype model verified this belief and showed that cooling rate did, in fact, actually exceed minimum specifications.

The proving tests, discussed in Appendix D, showed that the specimen could be cooled 65 degrees centigrade in a period of five seconds from an initial temperature of 600 degrees centigrade. An air flow rate of 20 cubic feet per minute was used. Further cooling gave a 200 degree centigrade drop in 25 seconds.

Temperature Measurement

It is necessary to monitor temperature as close to the test specimen as possible. Although provision is made for a two thermocouple moni-

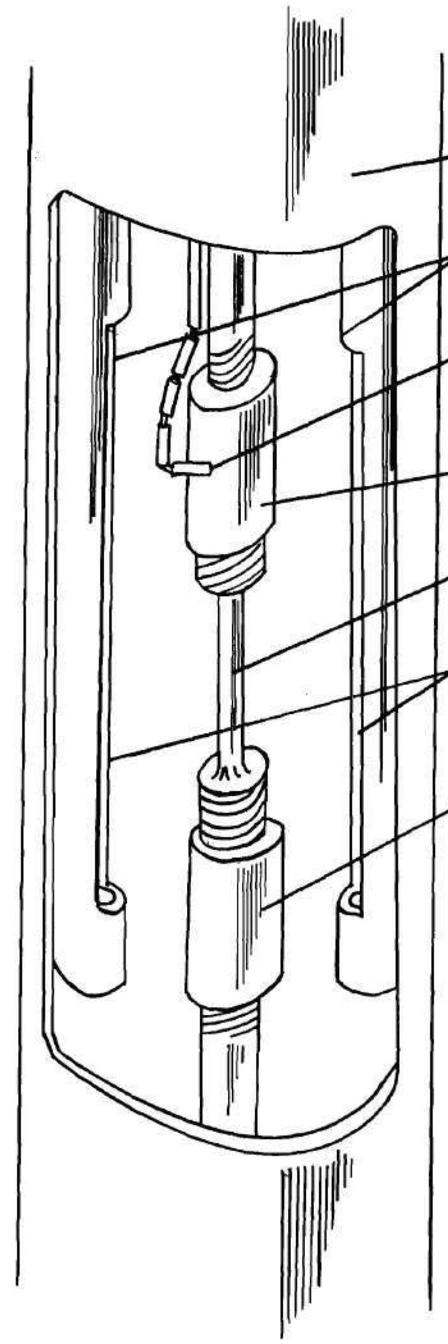


Figure 4. View Showing Relation of Delivery Pipes to Test Specimen.

toring system, normal operation required only one which enters the vacuum chamber through the upper connector. Ceramic insulation is placed in two holes drilled axially in the upper connector and wires run through this insulation and out into a larger hole in the side of the piece. The wires then pass through a rubber stopper plugged into the side of the upper connector and are sealed with Glyptal once the thermocouple is in place. Without proper sealing, leaks develop at the stopper and the high vacuum is lost. Once sealed in place, the stopper will not come loose under normal operation and require no special holding device.

Chromel-alumel thermocouples are used for temperature monitoring. This thermocouple material will not be appreciably effected by movement or oxidation under anticipated operating conditions.

Assembly

The general assembly of the device is shown in Figure 3. No particular tight tolerances in assembly are observed. Details of assembly are discussed in Chapter IV.

CHAPTER IV

UNIT OPERATION

Installation

The installed unit is shown in Figures 4 and 5 which is the arrangement necessary for routine tensile tests. The entire unit fits directly on the crosshead of the Instron Instrument and requires outside connections to a power supply, a vacuum system, and an air or inert gas supply. Furnace installation has been discussed in a previous section.

The test specimen screws into two mounting collars on the pulling assembly. A thermocouple is installed through the upper piece in the pulling assembly and the temperature sensing junction fastened to a point near the test specimen. Lead wires for the thermocouple pass through an exit port in the upper connector and are held away from the metal surface by a rubber plug. The wires pass through the plug which fits firmly in the hole and is sealed with Glyptal to prevent vacuum leaks. Under normal tests a second thermocouple is not used and the lower connector in the pulling assembly is sealed with a solid rubber stopper. All components of the pulling assembly are fitted together as a unit before being mounted in the vacuum capsule.

The top plate of the vacuum capsule is bolted to the flange after an "O" ring has been placed in a groove in the flange. An aluminum collar is screwed on the fitting extending from the top plate.

The end of the pulling assembly is inserted through the top plate,

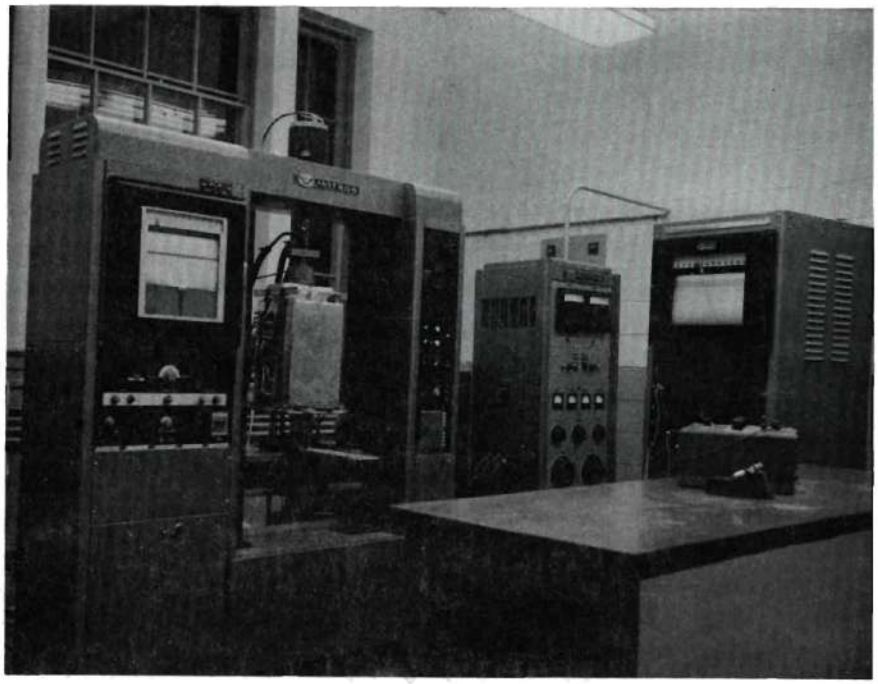


Figure 5. Front of Installed Instrument Showing Apparatus for Proving Tests.

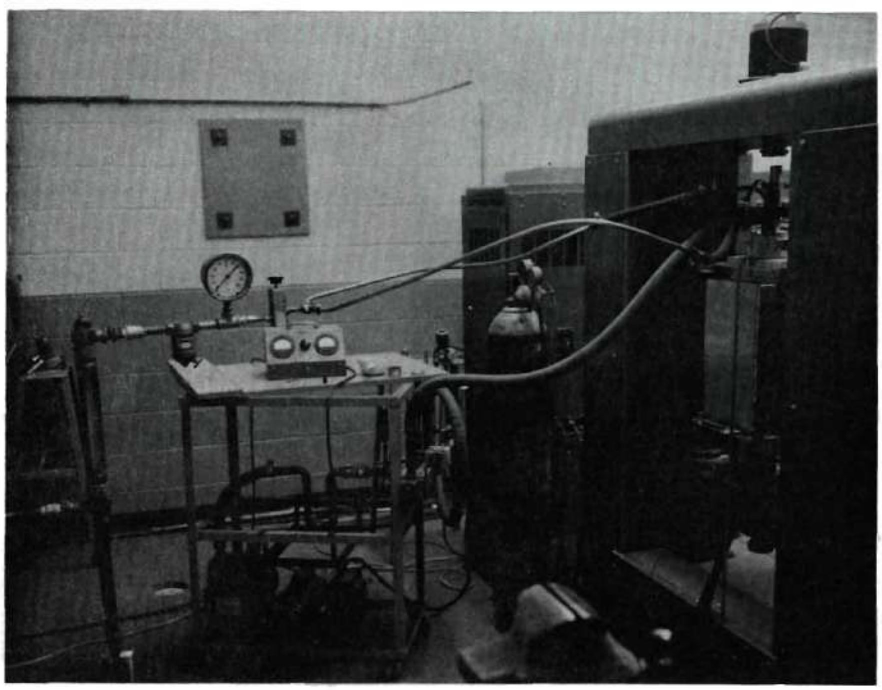


Figure 6. Rear of Installed Instrument Showing Vacuum Pump, Air Measuring Instrument, and Piping.

through the vacuum capsule, and out through a plug at the base of the vacuum capsule. After the furnace has been moved from the center position of the Instron Instrument crosshead, the assembled vacuum capsule is passed directly through the furnace core. The furnace is rolled back to its original position and the lower connector screwed into the fitting on the Instron Instrument crosshead. A special shim is fitted onto the lower connector and is bolted to the plug in the vacuum capsule. This shim supports the vacuum capsule and locks the capsule and lower connector together. Movement of the vacuum capsule during tensile tests is thereby prevented.

The vacuum system is attached to the exhaust port of the vacuum capsule, the cooling gas supply attached to the free ends of the two air delivery pipes, and the thermocouple lead wires attached to a millivolt measuring device. Strips of asbestos cloth are wound about the upper part of the vacuum capsule to provide a snug fit between the capsule and the top brick of the furnace. By minimizing air flow through the core, the wrapping insures faster specimen heating and tighter temperature control. A cooling collar, connected to an air supply, is installed about the top of the vacuum capsule to prevent the top "O" rings from overheating.

Operating Instructions

The test specimen is first mounted in the vacuum capsule as described in the previous section. The collar on the upper plate of the vacuum capsule is raised so as to provide support for the pulling assembly at testing temperatures. All valves are then closed, a plug inserted in the hole in the vacuum line, and the vacuum system turned "ON". The furnace is then set to an approximate desired temperature and turned "ON".

Exact specimen temperature is monitored by the thermocouple inserted in the vacuum capsule and must be consulted for exact specimen temperature. The furnace temperature control must be adjusted in conjunction with the indicated specimen temperature to obtain a correct desired specimen temperature. The furnace tends to overshoot the set temperature on the furnace control so that care must be taken to prevent the test specimen from overheating.

When the actual tensile test is ready to be run the crosshead is moved up and the upper connector guided into the collar on the Instron Instrument. A pin is then placed through the collar and the upper connector of the pulling assembly so that a load can be applied through the pulling assembly to the test specimen.

Just before quenching the specimen the vacuum system should be shut off by closing the valve at the vacuum pump to prevent 300 degree centigrade air from passing through the pump. The actual quenching involves simultaneously removing the plug from the vacuum line and turning on the air supply. Full pressure from a standard 1/2 inch air line at 100 pounds per square inch gauge can be tolerated. Full air flow will give faster cooling and will not harm the instrument or test specimen.

It is recommended that the Instron Instrument be set to give a continuous preset maximum load during quenching. Cooling the sample results in thermal contraction of the specimen and a corresponding stress rise if free movement is not permitted. If the thermal contraction is not compensated for by special Instron Instrument settings the resulting stress level in the specimen will give an excess load level and possible permanent deformation.

The specimen may be removed from the capsule by removing the shim and the Instron mounting from the bottom of the pulling assembly and drawing the assembly through the top of the capsule. If the sample has fractured, the bottom part of the pulling assembly may be drawn out through the bottom plug in the vacuum capsule. The sample should be removed from the furnace before it has a chance to reheat. Only the specimen itself is thoroughly cooled by the quench and the hot adjoining parts will cause the specimen to reheat.

Operating Characteristics

Primary interest in operating behavior centers about the quenching device. A series of tests using aluminum and brass simulated test specimens discussed in Appendix D shows that the required cooling rate was attained. Figure 7 shows the cooling curve that would be obtained if a test specimen was cooled from a temperature of 600 degrees centigrade by pressurized air having a mass flow rate of 20.3 cubic feet per minute. Maximum cooling rate is attained less than one second after cooling begins and diminishes as the temperature falls.

No warpage or deformation of instrument parts were noticed during the series of proving tests. Cooling rate did not show an appreciable difference for either aluminum or brass indicating that high speed cooling is not limited to aluminum specimens. Nevertheless, both materials tested had high thermal conductivities which may have been a factor in preventing deformation of the sample. During cooling a temperature difference may exist between windward and lee points on the outside of the specimen. This temperature difference would be greater for a material with heat conduc-

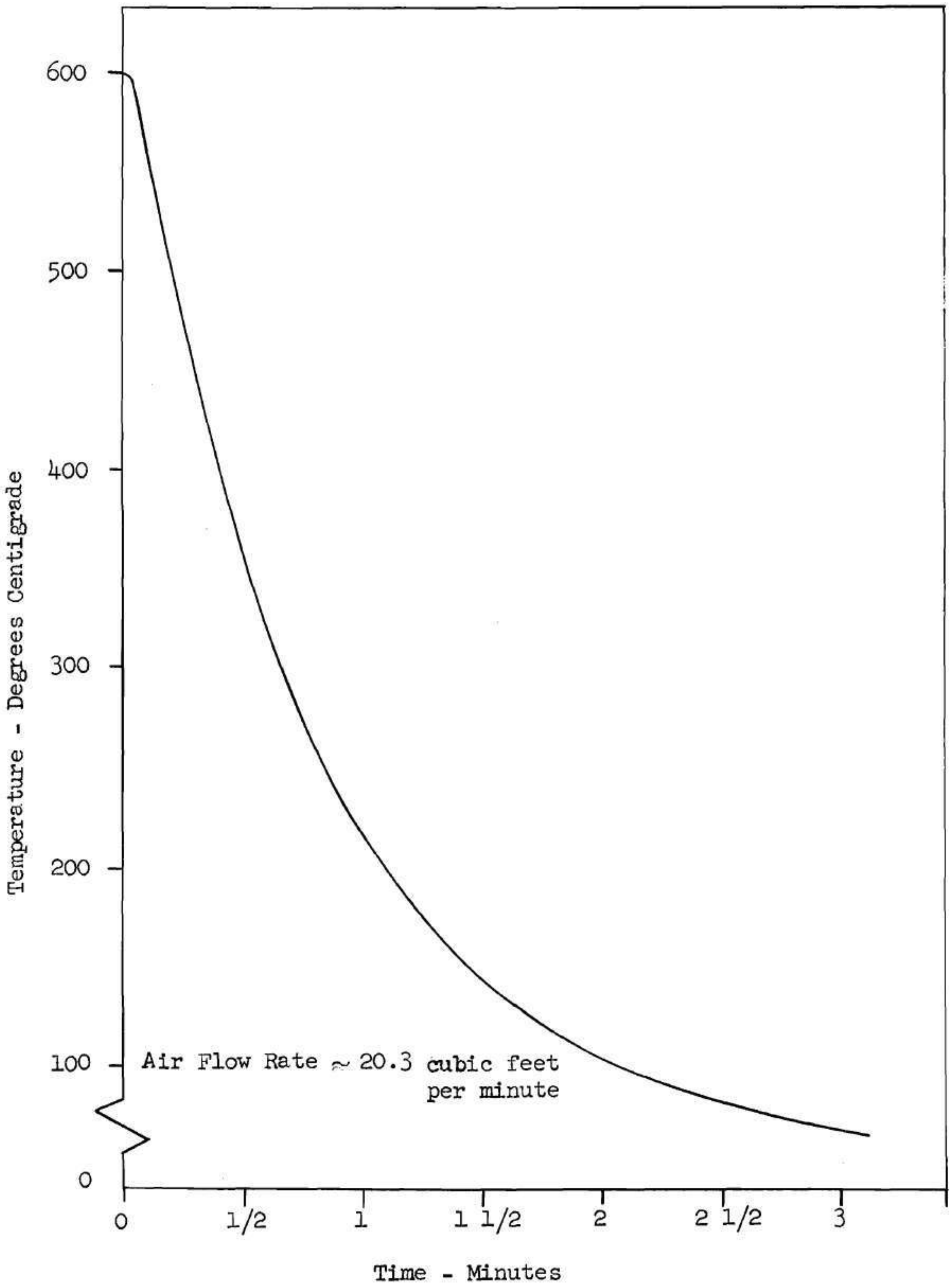


Figure 7. Cooling Curve for Test Specimen

tion properties lower than that of aluminum or brass.

The experiments showed the speed with which full cooling rate was reached. Figure 8 shows a typical cooling curve for the first ten seconds of cooling. Maximum cooling rate from a starting temperature of 617 degrees centigrade was reached less than one second following the start of cooling and was approximately 24 degrees centigrade per second. The rate decreased to approximately 10 degrees centigrade per second at the end of five seconds. In this five second period specimen temperature decreased 65 degrees centigrade. At starting temperatures below 500 degrees centigrade, however, a 50 degree centigrade drop in less than five seconds was unattainable, even with maximum air flow through the system.

Corrosion did not harm the instrument parts. During experimentation possible specimen oxidation may preclude the use of air as a cooling agent. In these cases quenching with an inert gas may be necessary. Such a gas, either argon or helium, should prove a successful quenching medium. Care should be taken to promptly remove the test specimen from the furnace once the experiment is finished or to sustain a low gas flow after the completion of the main cooling to prevent the specimen from reheating. Faster cooling could be attained by lowering the entering temperature of the cooling gas. A feasible method for doing this would be by passing the gas through coils emersed in an alcohol dry ice bath. Such a process would lower the gas temperature to approximately minus 70 degrees centigrade.

Use of Instrument

The general design of this instrument has been flexible so that

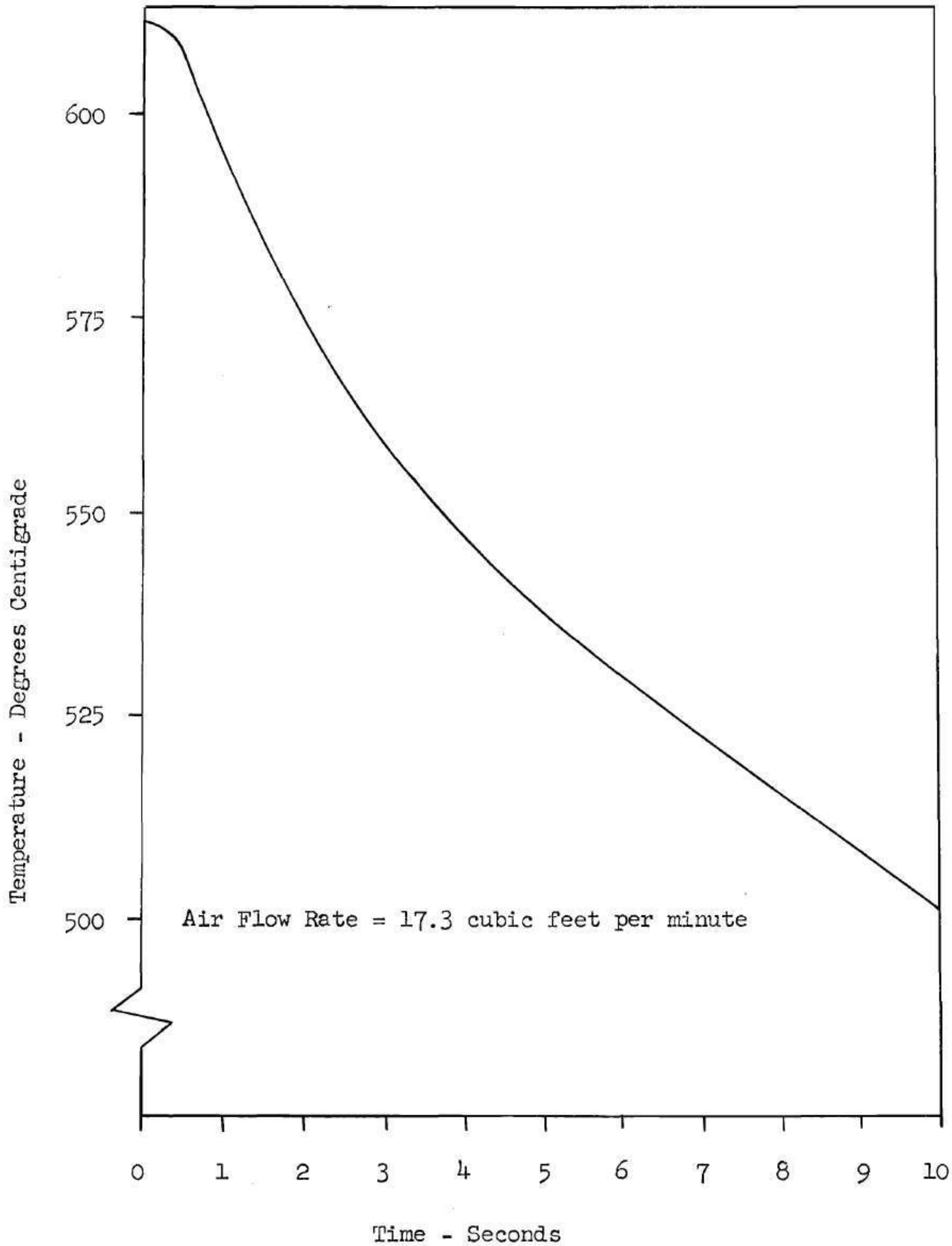


Figure 8. Cooling Curve for Test Specimen

several possible types of tensile tests can be run. Although high temperature work is somewhat limited by the low maximum temperature of the furnace (approximately 800 degrees centigrade) the furnace provides a uniform temperature zone approximately six inches long up to this temperature. Because air flow rate can be tightly controlled, cooling rates can be greatly varied making cooling studies of small samples under a tightly controlled tensile load possible. Tensile tests with tension, time, and temperature (controlled heating and cooling) variables are possible. This quenching mechanism, makes the instrument a versatile piece of laboratory equipment.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The design specifications were as follows: cool a standard size Instron vacuum capsule specimen at a rate of at least 10 degrees centigrade per second for the first five seconds of cooling and then 100 degrees per minute for the next two minutes from a temperature of 600 degrees centigrade. This requirement was reached and exceeded. From 600 degrees centigrade a 65 degree centigrade temperature drop in five seconds of cooling was achieved and a 200 degree centigrade drop was obtained in the next 25 seconds.

The general cooling curve for the test specimen is shown in Figure 9. Between 624 and 200 degrees centigrade maximum cooling rate is achieved one second following the start of cooling. For a set air flow rate the individual cooling curve will then intersect and follow a main cooling curve to approximately 80 degrees centigrade.

Recommended Modifications

There are several improvements that could be made to the instrument to ease operation. The basic quenching mechanism has been reliable and at the present time needs no modification. Improvements would consist of the following:

1. Support for the pulling assembly to eliminate all loads on the test specimen during the heating process.

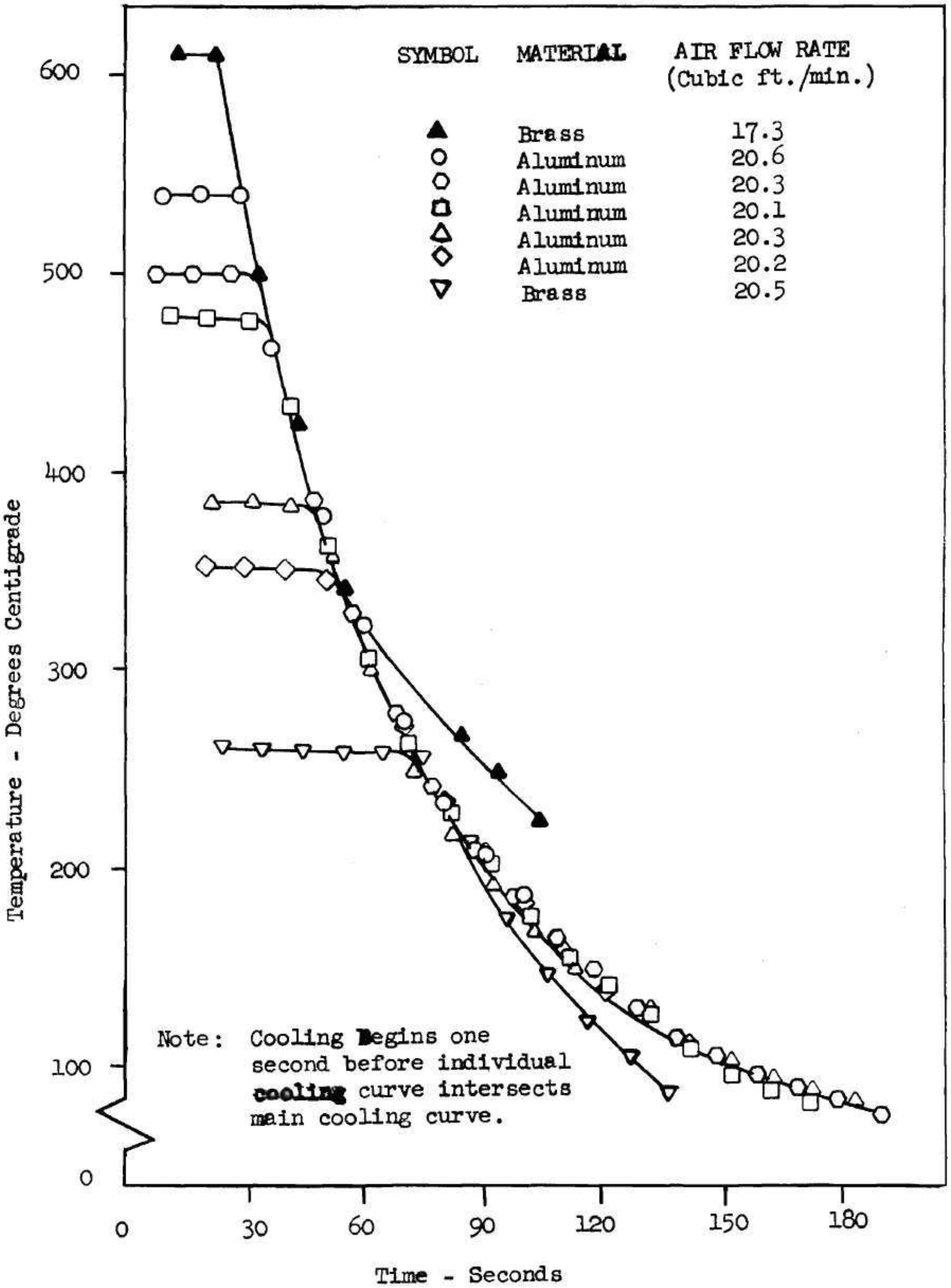


Figure 9. Cooling Curve for Test Specimen

2. An easier and faster way for mounting the thermocouple.

3. A support mounting on the furnace for holding the vacuum capsule during loading and unloading operations

4. Adjusting the vertical height of the delivery pipes to provide a more uniform temperature distribution in the test specimen during cooling.

These modifications would improve the design and workability of the instrument.

APPENDICES

APPENDIX A

FURNACE CALIBRATION

Three separate windings were used on the furnace core which produced three distinct temperature zones: top, middle, and bottom. By varying the current into each of the windings a longer zone of uniform temperature in the furnace core was anticipated than that which would have been available in a singly wound unit. Subsequently a system of eight iron-constatan thermocouples was constructed to determine temperature distribution in the furnace core. These thermocouples were inserted through the top opening of the furnace and allowed to hang freely in an air atmosphere in the core. They were spaced at two inch intervals beginning two and one-half inches down from the top of the furnace.

The thermocouple system was connected to an eight channel multipoint recorder and time-temperature curves of each point monitored by the thermocouples obtained. Powered asbestos was used to pack both top and bottom openings to lessen convective air currents passing through the furnace. The system was calibrated in two manners. The recorder was calibrated by feeding a known output from a millivolt potentiometer into a calibrating circuit. Thermocouples were checked for accuracy by emerging each individually into an ice bath and a container of boiling water, then checking EMF outputs against published values.

For this set of experiments the temperature control was set to 1,250 degrees Fahrenheit and the anticipator turned "ON". The anticipator is a device used to prevent temperature overshoot by the furnace and helps in maintaining constant temperature over long periods of time. The coils were set to various current ratings and the furnace allowed to heat up. Temperature distribution for representative heating trials are shown in Figures 10 and 11. Figure 10 shows heating characteristics for the furnace with each of the windings set to the same current reading. A zone of "uniform" temperature does exist and would be found between two points. They are six and one-half inches and ten and one-half inches from the top of the furnace. Taking these as the two outward points of "uniform" range, a temperature gradient of 16 degrees Fahrenheit is observed. Figure 11 shows heating characteristics when some attempt has been made to form a uniform temperature zone in the center of the furnace. For the same four inch zone as described in Figure 10, a temperature gradient of only nine degrees Fahrenheit exists while, if a 25 degree Fahrenheit temperature gradient can be tolerated, a zone six inches long is available. Although these temperatures are considerably higher than the control setting of 1,250 degrees Fahrenheit, it is not harmful since the control can be calibrated to give the desired temperature in the furnace itself. The temperature overshoot observed in both cases is due to thermal stabilization of the furnace. The anticipator held long term temperature constant once transient heating gradients in the furnace wall stabilized. Some degree of underdamping is to be expected in heating a furnace of large mass.

Further tests produced the data shown in Figure 12. Only six points are shown since end points fell off the calibrated recorder scale. The two top curves show the optimum uniform temperature distribution obtained in these tests. The second curve, that in which the top coil was

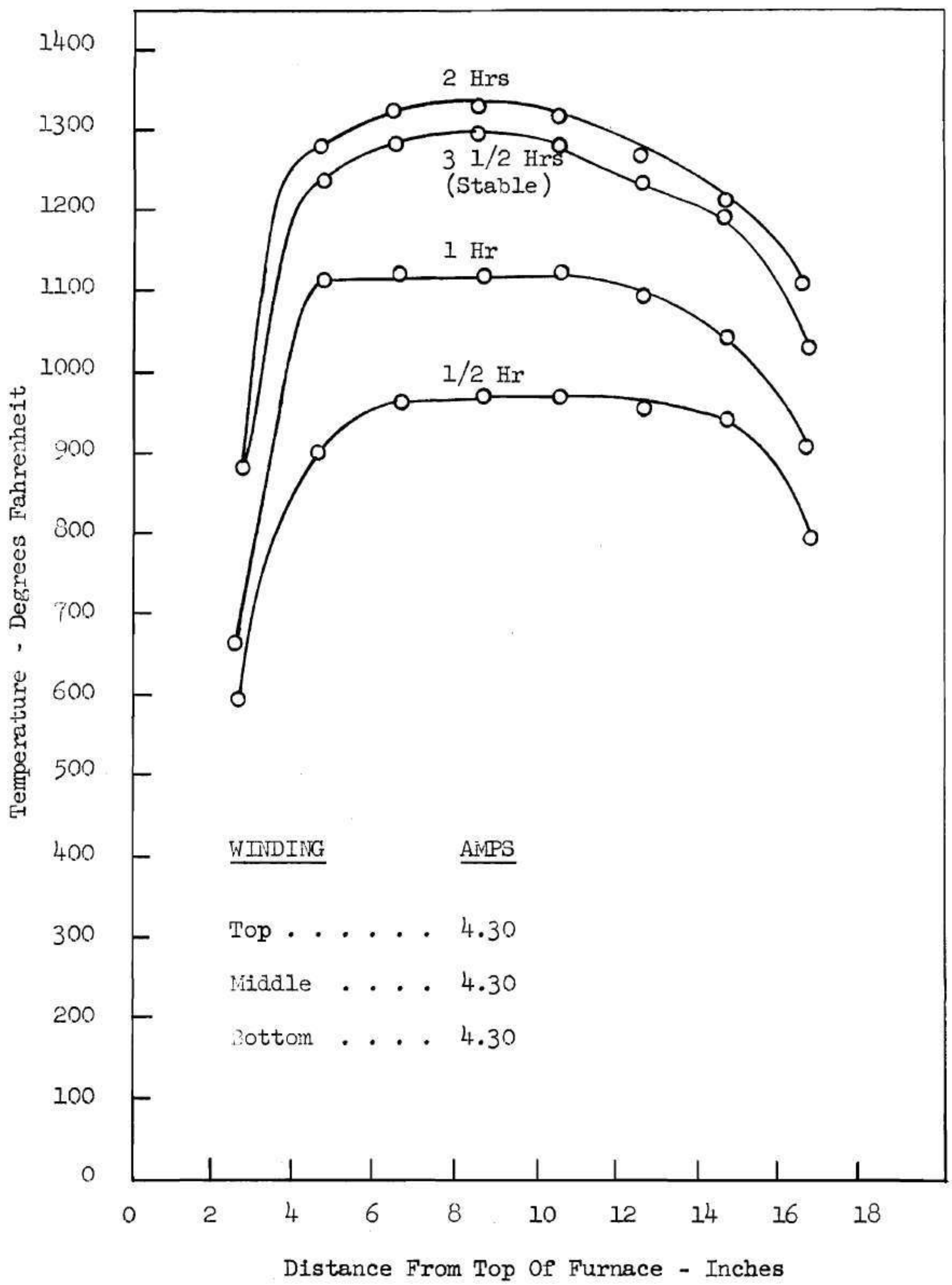


Figure 10. Furnace Calibration Curve

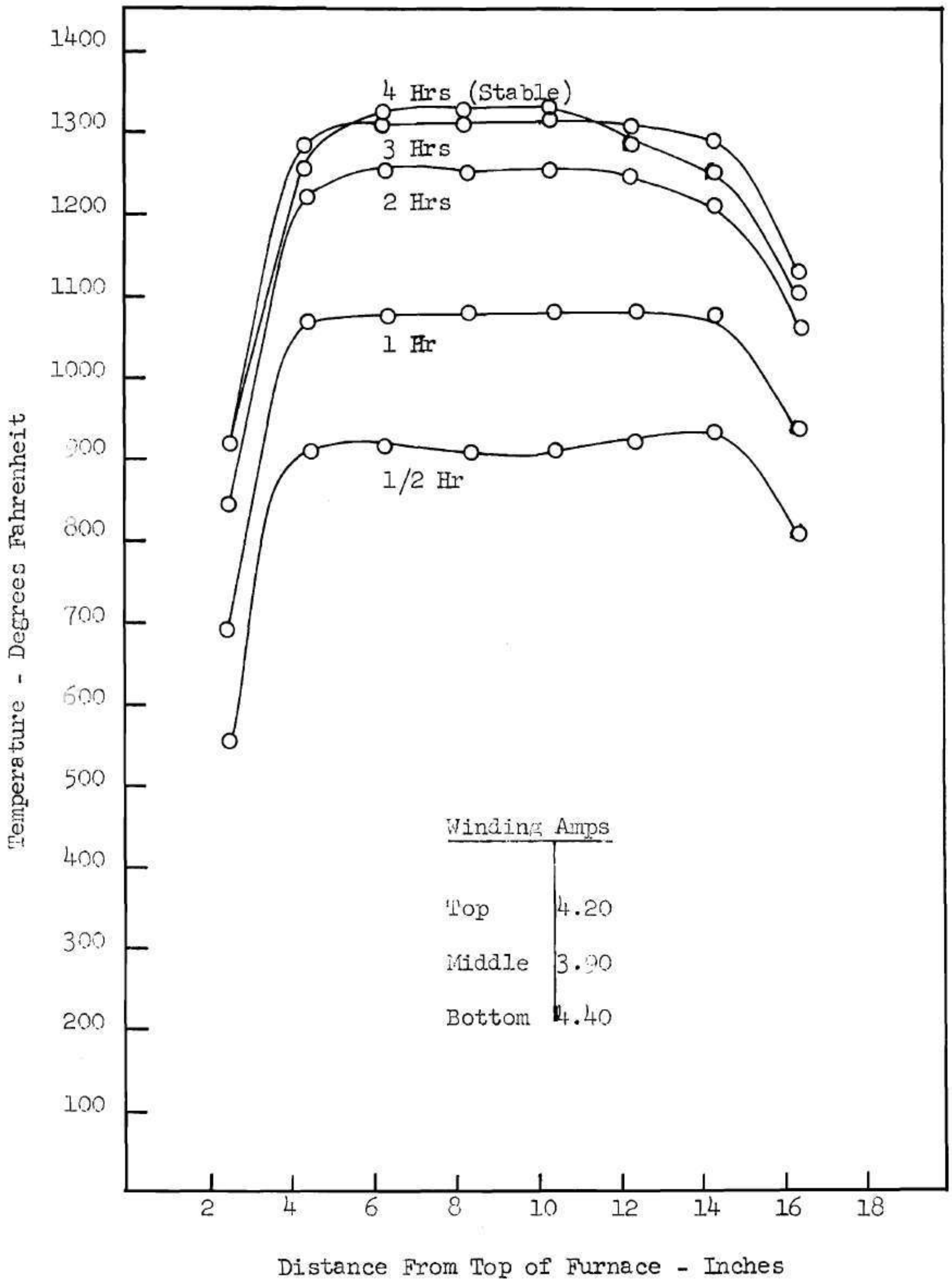


Figure 11. Furnace Calibration Curve

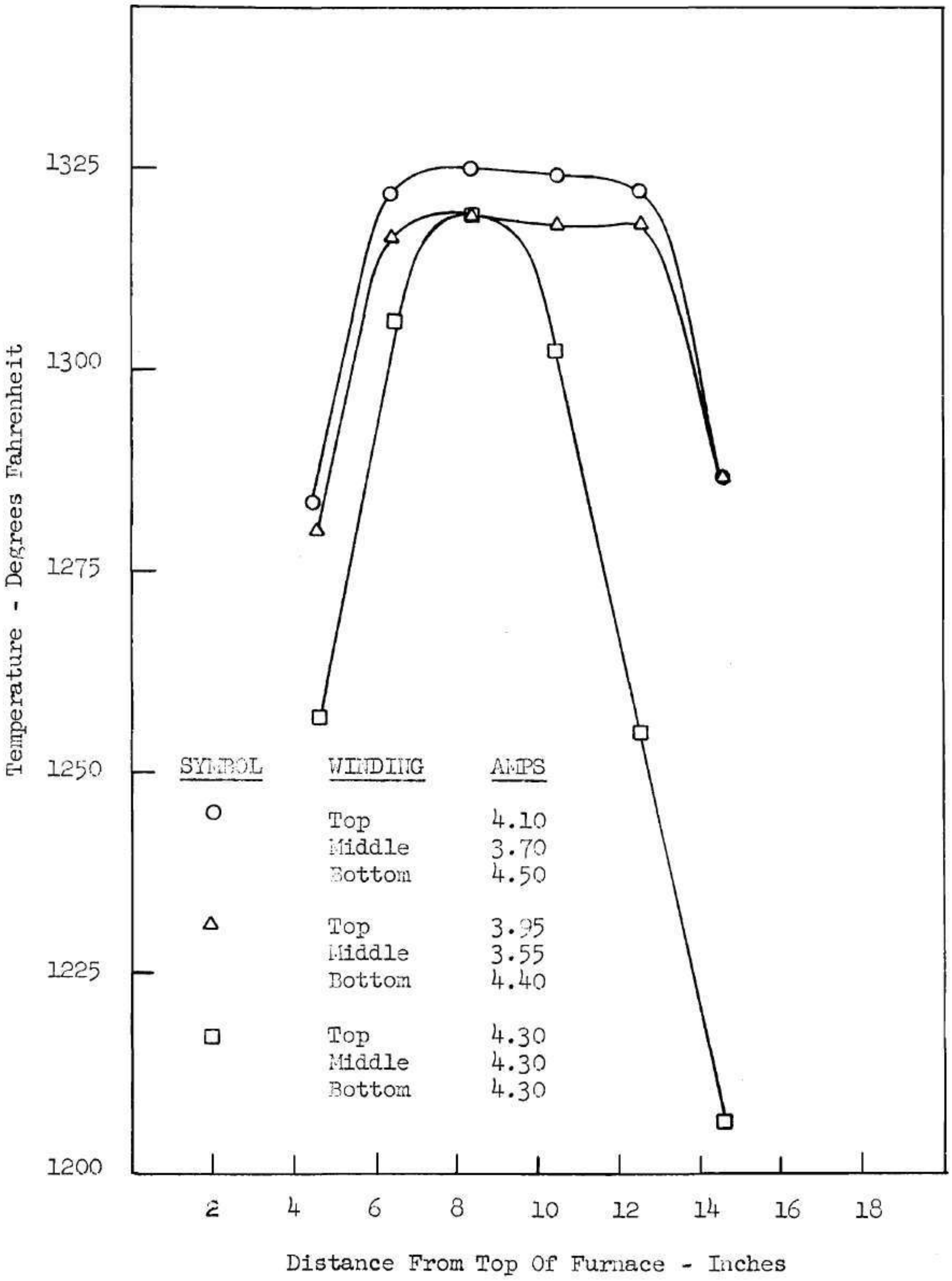


Figure 12. Furnace Calibration Curve

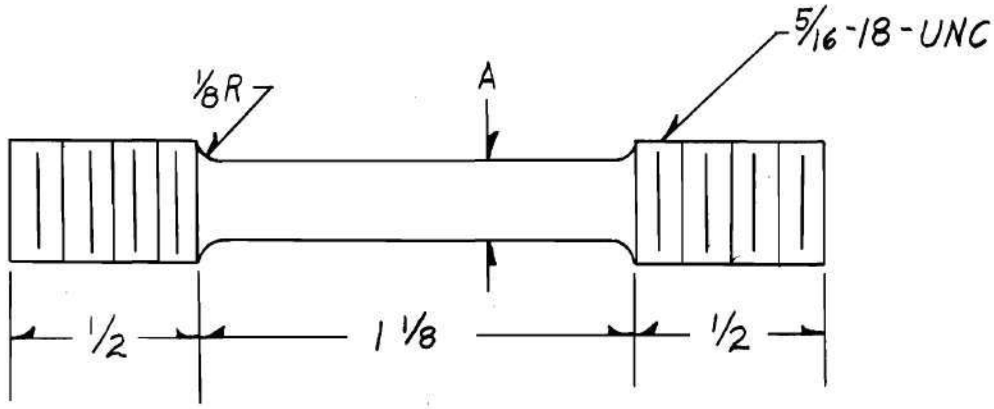
set to 3.95 amps, gives a temperature variation of plus or minus one and one-half degrees Fahrenheit over a six inch segment of the furnace. In contrast, the lower curve, that in which the furnace acted as a single coil, shows a 64 degree Fahrenheit difference over the same segment. The uniform temperature zone extends from a point six and one-half inches to a point twelve and one-half inches below the top of the furnace. The optimum current setting gives 3.95 amps to the top coil, 3.55 amps to the middle coil, and 4.40 amps to the bottom coil.

There is some question, however, as to whether the isothermal settings will give a uniform temperature distribution in a mounted specimen under test conditions. The vacuum chamber will effect specimen temperature distribution, particularly by completely eliminating convective air currents on the surface of the specimen. Engel[6] has shown that identical current settings give different temperature profiles in a vertical tubular furnace when vacuum is substituted for a gas atmosphere. Although a series of tests in which actual specimen temperature was monitored (Appendix D) showed a one-half inch section of the specimen isothermal to plus or minus one degree centigrade under stable conditions, no attempt was made to determine temperature variation between the ends of the specimen. An experimentor needing critical temperature control is advised to test with a dummy specimen of sample material to determine if the temperature difference between the two ends falls within allowable tolerances. If not, recalibration of isothermal settings will be necessary.

APPENDIX B

TEST SPECIMAN

Figure 12 shows the dimensions and specifications of a test specimen to be used in this instrument.



Scale: 2" = 1"

A = 0.113 + 0.001 inches for 0.01 square inches
= 0.160 + 0.001 inches for 0.02 square inches

Figure 13. Test Specimen

APPENDIX C

COOLING CALCULATIONS

Operating characteristics of this instrument cannot be accurately determined from a purely mathematical study. Mathematical anologies to the physical system are difficult to draw because of transient temperature gradients in the material and complex air flow patterns in the vicinity of the test specimen. It was necessary, however, to determine roughly if gas cooling could be used before building a prototype for test operations.

An analysis was made, for the purpose of indicating feasibility, on cooling an aluminum test specimen 10 degrees centigrade per second for five seconds from an initial temperature of 600 degrees centigrade. For analysis, two principal assumptions were made:

1. Only a critical area was cooled (Figure 14).

2. An estimate of temperature distribution at the end of five seconds could be made and the analysis reduced, for that instant only, to a steady state problem. A time dependent analysis over the five second cooling period could be thereby eliminated.

The 10 degree centigrade per second cooling rate occurs only during the first five seconds. A critical area for cooling is defined in Figure 14. Inspection shows that cooling is by forced convection of a gas released from two delivery pipes. While being cooled, the critical area is also heated by conduction through the rod and radiation from the surrounding pipe.

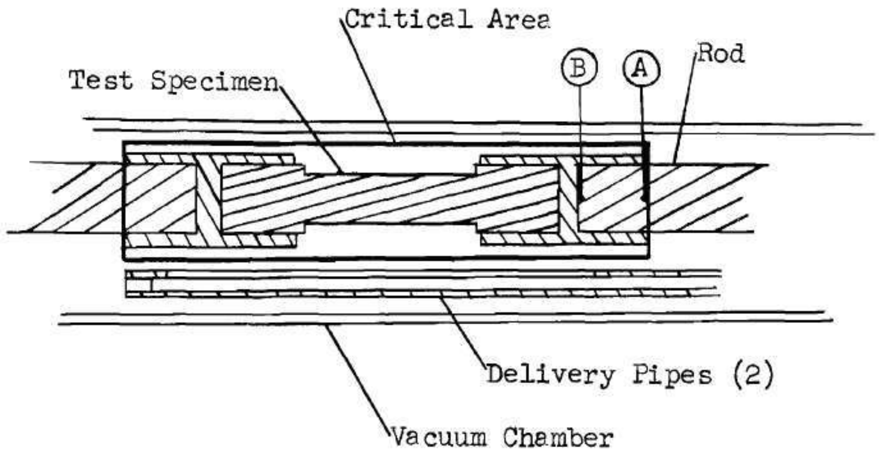


Figure 14. Cross Section of Vacuum Tube Showing Critical Cooling Area.

During the first five seconds the test specimen temperature drops from 600 to 550 degrees centigrade. In the critical area there are 0.0103 pounds of aluminum and 0.0800 pounds of Inconel. Specific heat of the two metals are compared below:

c_p aluminum = 0.30 BTU per pound mass degree Fahrenheit.

c_p Inconel = 0.12 BTU per pound mass degree Fahrenheit.

This means that for a 50 degree centigrade drop 1.020 BTU must be removed. Taken over a five second period this gives 0.204 BTU per second for the average direct heat loss rate.

Heat gain into the critical area from conduction is first determined. The outer edge of the critical area (Point A, Figure 14) is assumed to be 600 degrees centigrade and a point 0.500 inches toward the specimen (Point B, Figure 14) is assumed to have dropped to 550 degrees centigrade. Conduction through this area is determined by evaluating physical properties at 600 degrees centigrade. A conduction formula is used:

$$q_{kb} = -2kA \frac{dT}{dx}$$

where

q_{kb} = rate of heat gain by conduction from both ends

k = thermal conductivity

A = cross sectional area

dT = temperature gradient

dx = distance gradient.

Evaluation shows that the rate of heat gain from conduction is 0.0197 BTU per second. Heat gain from radiation is determined by assuming the entire critical area to be 500 degrees centigrade and the surrounding pipe to be 600 degrees centigrade. The general radiation formula is used:

$$q_r = \alpha A \sigma T^4_{\text{pipe}} - \epsilon A \sigma T^4_{\text{critical area}}$$

where

q_r = rate of heat gain by radiation

α = absorptivity $\approx$ 0.9 Inconel Parts
$\approx$ 0.2 Aluminum Specimen

ϵ = emissivity $\approx$ 0.9 Inconel Parts
$\approx$ 0.2 Aluminum Specimen

A = surface area of critical area

σ = Stefan Boltzmann constant

T = respective absolute temperatures.

The rate of heat gain into the critical area from radiation is 0.0125 BTU per second.

The net heat removal rate at five seconds is the sum of average direct heat loss rate, conduction heat gain rate, and radiation heat gain rate. The summation shows the net heat removal rate is 0.236 BTU per second. It is assumed that heat must be removed from the critical area at this rate for the first five seconds of cooling.

It is now necessary to determine if a gas can give the necessary cooling. Helium is used in calculations since it is an inert gas and may be used when elimination of oxidation of the sample is desired. It is assumed to enter the delivery pipes at 3 atmospheres pressure and 15.5 degrees centigrade temperature, leave the delivery pipes at 260 degrees centigrade, and rise 75 degrees centigrade across the critical area. These assumptions are checked later.

The specific heat of helium is 1.24 BTU per pound mass degree Fahrenheit. At three atmospheres pressure and 260 degrees centigrade it has a density of 0.0174 pounds mass per cubic foot. Using the assumed temperature rise of 75 degrees centigrade a cooling potential of 2.91 BTU per cubic foot of helium exists. To remove 0.236 BTU per second from the critical area, 0.0445 cubic feet per second of helium at 3 atmospheres pressure and room temperature must be supplied. The helium passes through two, one-quarter inch pipes (inside diameter = .375 inches). Helium velocity through the pipes is 43 feet per second based on 3 atmospheres pressure and 140 degrees centigrade temperature (the average temperature in the delivery pipes).

It is necessary to see if, in passing the critical area, the helium absorbs enough heat to rise in temperature the assumed 75 degrees centigrade. The first step in providing a check is to verify the assumed temperature at which helium leaves the delivery pipes.

The delivery pipes are first divided into a series of zones as shown in Figure 15[1]. The pipe temperature for each zone is extrapolated from data under similar conditions. The procedure begins by analyzing zone 1 and the properties of helium upon entering the zone. Based on an average velocity of 40 feet per second and a smooth pipe, Reynolds number is first calculated. It is found to be approximately 3,100 and in the transition region. Since actual velocity at entry is below average velocity, flow will be assumed near laminar and the analysis of heat transfer in the pipes based on laminar relations. Prandtl and corresponding corrected Nusselt numbers are determined using laminar relations[7] and an average heat transfer coefficient calculated making use of the definition of Nusselt number. Since the heat transfer coefficient, area of heat transfer, and mass volume flow of helium are now known, the rise in gas

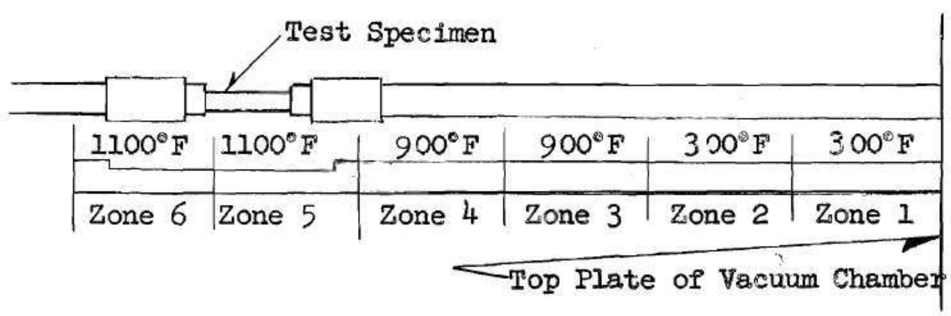


Figure 15. Division of Delivery Pipe for Temperature Estimation.

temperature can be calculated. The new temperature is then used for evaluating physical properties of helium as it enters zone 2. The procedure is repeated until the temperature of the gas leaving the delivery pipes at the end of zone 5 is determined. The heat transfer coefficient and temperature at the end of each zone are tabulated in Table 1.

Table 1. Calculated Temperatures at the End of Three Inch Divisions in Delivery Pipe.

Zone	Heat Transfer Coefficient (BTU/hr. ft.^{2} °F)	Temperature at End of Zone - °C
Entry	-	15.5
1	21.4	32.2
2	21.2	48.8
3	21.2	83.8
4	20.7	144
5	17.3	251

Using the analogy of a cool gas passing across a heated cylindrical solid, heat transfer from the critical area is obtained. This is by no means an accurate analogy but is offered for approximation purposes. Flow into the area is through a 1/8 by 3 inch slot in each of the two delivery pipes. By evaluating gas properties at 260 degrees centigrade and 2 1/4 atmospheres pressure (an assumed pressure drop), helium velocity of approximately 10 feet per second is calculated. A heat transfer coefficient is determined by first solving an equation for passing over a cylinder[7].

$$\frac{h_{c\theta}D}{k_f} = 1.14\ (V_\infty D_o/v_f)^{1/2}\ Pr_f^{\,0.4}(1 - (\theta/90)^3)$$

where

$h_{c\theta}$ = heat transfer on section of cylinder

D_o = diameter of cylinder

k_f = thermal conductivity of fluid

V = velocity of gas

Pr_f = Prandtl number

θ = angle measured from center of cylinder

v_f = kinematic viscosity

The critical area is divided into a three section cylinder. The small diameter portion of the test specimen forms one section and the large diameter ends and collars the other two. The equation is solved for several points on the circumference of the cylinders and an average heat transfer coefficient determined for each section. Knowing the average heat transfer coefficient, and the temperature difference between parts in the critical area and the cooling gas, an overall heat transfer of 0.316 BTU per second is calculated.

A maximum of 0.316 BTU per second can be removed by the gas as compared to 0.236 BTU per second calculated on an assumed helium temperature rise of 75 degrees. The discrepancy could indicate that the initial assumption was wrong and a slightly lower gas flow rate than was originally estimated would exist. However, the 0.316 BTU per second heat transfer rate was based on an infinite supply of gas. Actual heat transfer will be lower than this indicated figure, so that gas flow rate will approach the rate based on the 75 degree centigrade temperature rise for helium.

Flow rate of the helium will approximate eight cubic feet per minute at one atmosphere pressure and 60 degrees Fahrenheit temperature. The calculations thereby indicate that the required cooling rate for the first five seconds can probably be achieved. The building of a prototype is thereby justified.

APPENDIX D

OPERATING TESTS

The specifications on the cooling rate of the test specimen are as follows: from an initial temperature of 600 degrees centigrade it must be cooled 50 degrees in five seconds; it must then drop in temperature at the rate of 100 degrees centigrade per minute for the next two minutes. Faster cooling is desired but is not considered a design requirement.

A series of tests was performed to determine the cooling characteristics of a test specimen. A simulated test specimen was inserted into the instrument, heated under vacuum, and air quenched. Air flow rate and specimen temperature were recorded during each test.

A simulated test specimen was built as shown in Figure 16. Two thermocouple wells were drilled into the sample and 28 gauge ceramic insulated chromel-alumel thermocouples inserted. Both thermocouples were fed out through the pulling assembly, one through the top piece and the other through the bottom. The sample was installed in the mounting collars, the pulling assembly inserted into the vacuum tube, the vacuum tube dropped through the furnace core, and the unit secured to a mounting on the Instron Tensile Test Instrument. An air line was attached to the two delivery pipes and a vacuum line attached to the exhaust port. All valves were closed, joints sealed with Glyptal to prevent air leaks, the vacuum system turned on, and sealing checked until a vacuum of 10 microns or less was attained.

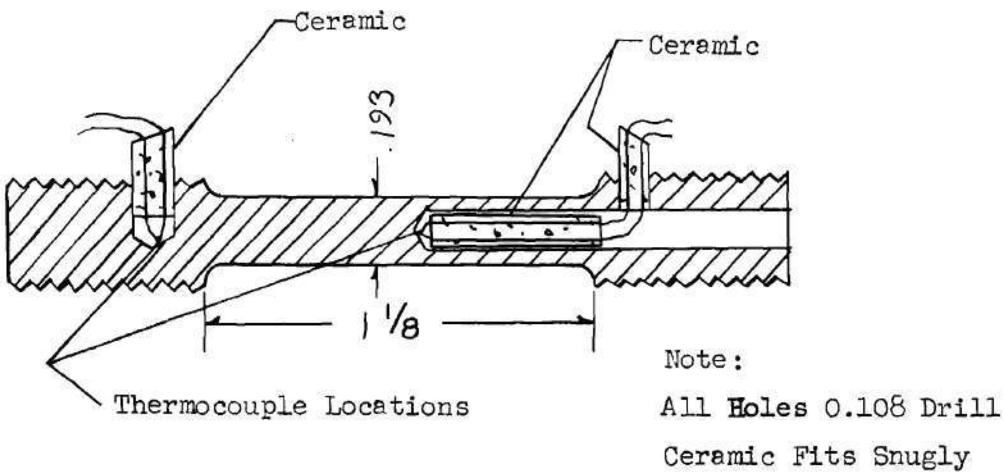


Figure 16. Simulated Test Specimen Cross Section

The thermocouple leads were attached to a switch which led to both a multipoint recorder and an oscilloscope. This enabled specimen temperature to be observed and recorded on two measuring devices. Both multipoint recorder and oscilloscope were calibrated with a known EMF from a millivolt potentiometer. Photographs of equipment and testing arrangement are shown in Figure 5 and 6.

The furnace was then set to an approximate desired temperature and turned on. Specimen temperature was monitored on the multipoint recorder and the temperature controller adjusted until a desired test temperature was reached. The actual test was then run.

One of the thermocouples was switched to the oscilloscope input and a camera set to photograph the oscilloscope screen. The other thermocouple output continued to be recorded on the multipoint recorder.

The furnace was first switched "OFF" and the valve between the vacuum pump and exhaust port closed. The first of two valves on the air line was opened so that only a vacuum valve separated the air supply and vacuum capsule. The operation took approximately 20 seconds during which no drop in specimen temperature was noted. Then, simultaneously, a plug between the exhaust port and the closed valve in the vacuum line was removed and the air supply turned "ON". Air flow rate and pressure upon entering the vacuum capsule were noted. Cooling continued for over two minutes. The air supply was then turned "OFF", vacuum restored to the system, and the specimen heated to another test temperature.

The air flow was metered by a volumetric flow rate indicator and a pressure gauge. The flow rate indicator was a commercial unit using a graduated vertical metering tube-float arrangement with an air capacity of 8.8 cubic feet per minute. Direct flow readings based on 14.7 pounds per square inch, 100 degree Fahrenheit air were visually made. The pressure gauge was a linear scale 0 to 100 pounds per square inch device which was directly read. By correlating indicated flow rate and true pressure readings, true flow rate was determined.

Figure 9 shows test results over a range of 625 to 80 degrees centigrade. These results come from the thermocouple mounted in the center of the test specimen. The thermocouple in the threaded head indicated an even faster cooling rate. For each test run shown in Figure 9 cooling of the sample began approximately one second before the individual cooling curve intersects the main cooling curve. An approximate single cooling curve for a specified air flow exists between 625 and 200 degrees centigrade. In this range, the cooling rate is roughly independent of the initial specimen temperature, and depends only on instantaneous specimen temperature. The generality holds after the first second of cooling. Changes in air mass flow rate do, of course, change cooling characteristics. The cooling curve starting from 615 degrees centigrade had an air mass flow that was 15 per cent less than the other air mass flows shown. It did not deviate appreciably from the general cooling curve until specimen temperature reached approximately 320 degrees centigrade.

It was observed that a temperature gradient existed through the length of the test specimen during cooling. The difference in the temperature recorded by the two thermocouples mounted in the dummy specimen reached a maximum of 35 degrees centigrade as shown in Figure 17. The entire unit was disassembled to determine the reason for the temperature difference. It was observed that gas flow concentrated at the lower end of the slots in the delivery pipe. This accounts for a build-up of cooling gas at the lower end of the test specimen and the faster cooling rate observed there. A modification consisting of either blocking off the lower portion of the slots or adjusting the height of the delivery pipes should result in a more uniform temperature distribution in the test specimen. Such a modification is recommended if tighter temperature control is desired.

The tests showed that the required cooling rate can be achieved. From an initial temperature of 600 degrees centigrade, with an air flow of 20.3 cubic feet per minute, the specimen temperature drops 65 degrees in five seconds. The remaining 200 degree temperature drop takes approximately 25 seconds, considerably faster than the two minute requirement.

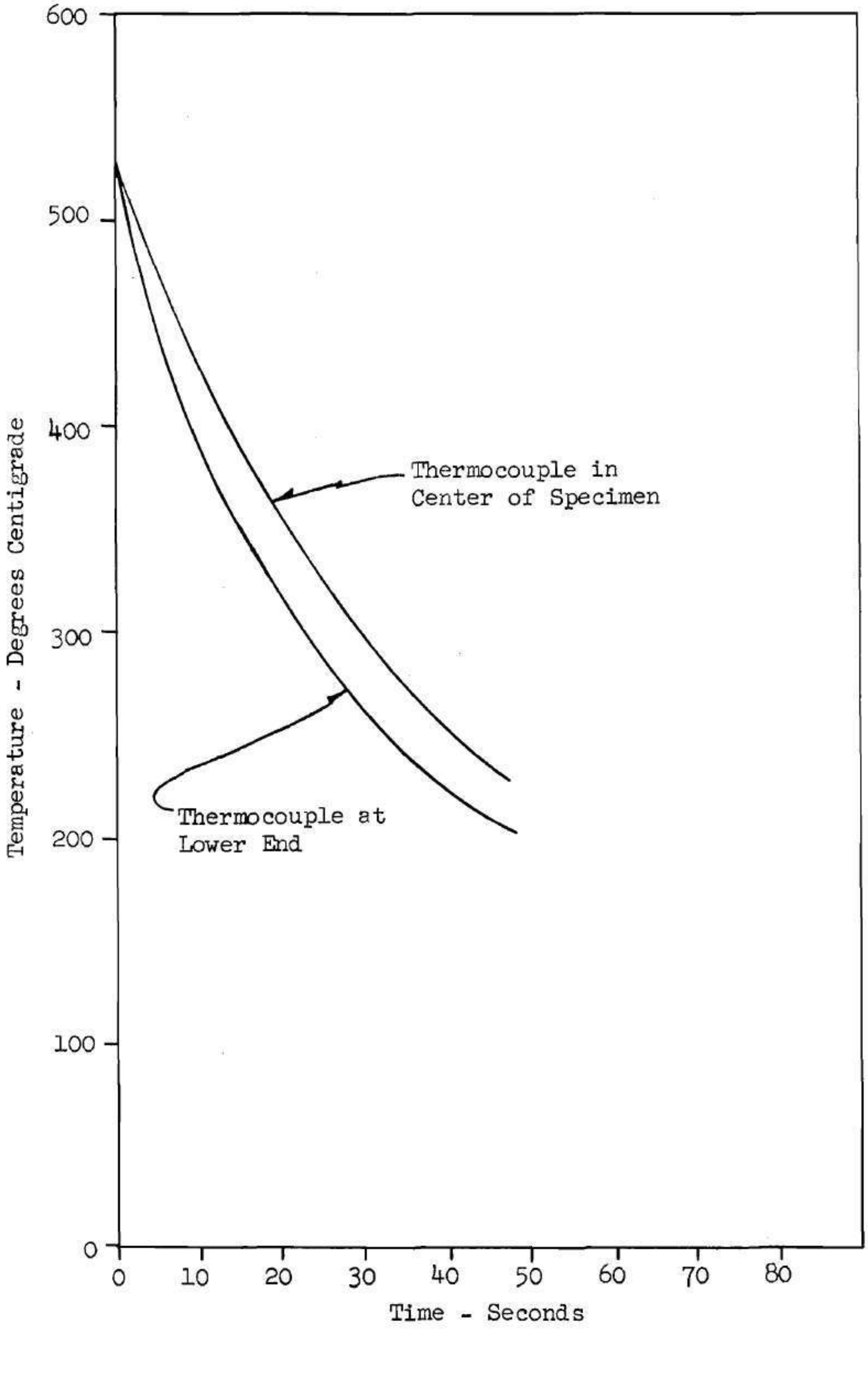


Figure 17. Temperature Difference Across Length of Test Specimen

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